AFRL-HE-WP-TR-2007-0114

Dynamic Characteristics and Human Perception of Vibration Aboard a Military Propeller Aircraft

Suzanne D. Smith
Jenny G. Jurcsisn
Anne Y. Walker

Biosciences and Protection Division
Biomechanics Branch

Jeanne A. Smith
David R. Bowden

General Dynamics Company AIS
5200 Springfield Pike, Suite 200
Dayton OH 45431-1289

September 2007

Final Report for July 2004 to August 2007

Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

NOTICE AND SIGNATURE PAGE

AFRL-HE-WP-TR-2007-0114

//SIGNED//

SUZANNE D. SMITH Work Unit Manager
Biomechanics Branch

//SIGNED//

MARK M. HOFFMAN, Deputy Chief
Biosciences and Protection Division
Human Effectiveness Directorate
Air Force Research Laboratory

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 074-0188

1. REPORT DATE (DD-MMM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From – To)
September 2007	Final Report	15 July 2004 – 30 August 2007

4. TITLE AND SUBTITLE
Dynamic Characteristics and Human Perception of Vibration Aboard a Military Propeller Aircraft

5a. CONTRACT NUMBER FA 8650-04-D-6472
5b. GRANT NUMBER N/A
5c. PROGRAM ELEMENT NUMBER 62202F

6. AUTHOR(S)
Jeanne A. Smith*, David R. Bowden*, Suzanne D. Smith**, Jennifer G. Jurcsisn**, Anne Y. Walker**

5d. PROJECT NUMBER 7184
5e. TASK NUMBER 02
5f. WORKUNIT NUMBER 15

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
General Dynamics AIS *
5200 Springfield Pike, Suite 200
Dayton OH 45431-1289

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command **
Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences & Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

10. SPONSOR / MONITOR'S ACRONYM AFRL/HEPA

11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-HE-WP-TR-2007-0114

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES
AFRL/PA cleared on 27 Sep 07 at AFRL/WS-07-2282.

14. ABSTRACT The dynamic characteristics and human perception of higher frequency multi-axis vibration associated with a military propeller aircraft environment were investigated. Triaxial accelerations were measured at the interfaces between the occupant and aircraft seat surface (seat pan and seat back) to evaluate and compare the effects of the aircraft seat fitted with different cushions. While all cushions showed a significant reduction in the X-axis seat pan vibration as compared to the original operational seat cushion at the blade passage frequency (BPF~73.5 Hz), the associated accelerations remained significantly higher than the floor input accelerations. Transmissibility data confirmed these seat system characteristics at higher frequencies. A body region perception survey suggested that the subjects were most sensitive to the BPF component of the operational exposure in contrast to the results for the weighted acceleration levels (ISO 2631-1: 1997). Effective multi-axis vibration mitigation strategies depend on the relationships between the location, direction, magnitude, and frequency of vibration entering the occupant and human perception of the exposure. Current human exposure guidelines may not optimally reflect these relationships for assessing higher frequency propeller aircraft work environments.

15. SUBJECT TERMS
whole-body vibration, propeller aircraft, seat cushions, prolonged exposures, frequency weightings, human vibration perception

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON: Suzanne Smith
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
U	U	U	SAR	35	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

This page intentionally left blank.

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This project was conducted as part of a Memorandum of Agreement between the Naval Health Research Center (NHRC), San Diego, CA, and the Human Effectiveness Directorate, Air Force Research Laboratory (AFRL/HE), Wright-Patterson AFB OH entitled "The Assessment of Biodynamic and Physiological Mechanisms and Mitigation in Military Operational Vibration Environments." The collection and assessment of the operational E-2C Hawkeye vibration used in this study was funded by the Office of Naval Research, Department of Navy, under Work Unit No. 63706N M0096.004-6813. The Navy point of contact was Dr. James Hodgdon, NHRC.

This page intentionally left blank.

SUMMARY

Rotary-wing and fixed-wing propeller aircraft can expose the occupants to prolonged periods of workplace vibration. Increasing reports of discomfort, annoyance, fatigue, and even back pain have been associated with increased vibration due to such factors as propulsion upgrades and longer exposures due to extended missions. Seat cushions have been considered a low-cost strategy for improving comfort and mitigating certain vibration, particularly for prolonged exposures. However, most studies have focused on low frequency vertical vibration. Limited information is available on the characteristics of higher frequency multi-axis vibration encountered during propeller aircraft operations and the effects of the aircraft seating system and components on the transmission of this workplace vibration to the occupant. The dynamic characteristics and human perception of higher frequency multi-axis vibration associated with a military propeller aircraft environment were investigated in the laboratory. Triaxial accelerations were measured at the interfaces between the occupant and aircraft seat surface (seat pan and seat back) to evaluate and compare the effects of the aircraft seat fitted with different cushions. While all cushions showed a significant reduction in the X-axis seat pan vibration as compared to the original operational seat cushion at the blade passage frequency (BPF~73.5 Hz), the associated accelerations remained significantly higher than the floor input accelerations. Transmissibility data confirmed these seat system characteristics at higher frequencies. A body region perception survey suggested that the subjects were most sensitive to the BPF component of the operational exposure. In contrast, the weighted acceleration levels (ISO 2631-1: 1997) suggested that the subjects would perceive the highest vibration in the vertical (Z) direction at the seat pan with substantial contributions in the X direction from the seat back, particularly at the propeller rotation frequency (PRF~18.5 Hz). The overall Vibration Total Value (ISO 2631-1: 1997) suggested that the operational exposures would be perceived as being “not uncomfortable” to “a little uncomfortable.” The results of this study suggest that current guidelines may not optimally reflect human perception of higher frequency vibration encountered during the operation of propeller aircraft. Even though seat and cushion designs may be able to significantly reduce the vibration of specific frequency components, the perceived

reduction is the key to effective mitigation. Newer seat designs, including active or semi-active vibration isolation mechanisms, may provide greater mitigation of higher frequency vibration as compared to a cushion alone. It is cautioned that a seating system or cushion that reduces vibration transmission to the occupant doesn't necessarily imply that the seat is more comfortable, and vice versa. The challenge is to design comfortable seating systems that are lightweight, crashworthy, and capable of reducing the transmission of vibration.

INTRODUCTION

Rotary-wing and fixed-wing propeller aircraft can expose the occupants to prolonged periods of workplace vibration. Back pain and backache have been documented in military aircrew who fly these aircraft. Although vibration has been suggested as a factor in the generation of these symptoms (Burmeister and Thoma, 1986; Shanahan and Reading, 1985), poor posture has been identified as the primary contributor, particularly in helicopters (Burmeister and Thoma, 1986; Pope, et al., 1986; Seris and Auffret, 1976, Shanahan and Reading, 1985). More recently, increasing reports of annoyance, fatigue, and even back pain have been associated with increased vibration due to propulsion upgrades and to the demand for longer missions. One particular case involved the two-engine, four-bladed U.S. Navy E-2C Hawkeye, a carrier-based early warning command and control platform. A survey of pilots/copilots and Navy Flight Officers (NFOs) revealed that 80 percent of those responding had experienced neck and/or back pain in a one-year period (Loomis, et al., 1999). Most of the respondents indicated that the pain lasted for at least one to two days. Thirty-five to forty percent considered the pain symptoms a limiting factor in job performance. Another case involved the four-engine, six-bladed C-130J and its variants. In the Weatherbird (one of the C-130 variants), the Aerial Reconnaissance Weather Officer and Dropsonde Officer were relocated from the flight deck to the cabin area, in close proximity to the propeller plane. There was concern that the higher levels of vibration in the vicinity of the propeller plane could lead to fatigue during prolonged missions. In general, military propeller aircraft can expose troops to levels of vibration that are not normally encountered in day-to-day civilian activities. A survey of the vibration levels in several military propeller aircraft is given in Smith (2006) and includes health and comfort assessments in accordance with the current international standard ISO 2631-1: 1997 for evaluating human exposure to vibration. One issue that has been raised is whether or not the comfort reactions and weighting curves given in the current ISO guidelines are appropriate for assessing exposures to the higher frequency vibration associated with the aircraft propulsion system (Smith, 2006).

Seat cushions have been considered a low-cost strategy for improving comfort and mitigating certain vibration, particularly for prolonged exposures. Conventional seat cushions typically increase the transmission of low frequency vertical vibration to the occupant (< 10 Hz), but attenuate higher frequency vibration (Fairley and Griffin, 1986; Pope, et al., 1989; Smith, 1997; Smith, 1998). A study conducted by Smith and Loyer (2003) evaluated the transmission of vertical vibration between 1 and 80 Hz to occupants using a rigid seat and several military seat pan cushions. Certain cushions were found to substantially dampen vertical vibration at higher frequencies associated with propeller aircraft. However, propeller aircraft can generate substantial vibration in the horizontal directions, requiring the evaluation of multi-axis vibration characteristics. In addition, the aircraft seat structure, if not rigid, could influence the transmission of vibration to the occupant and affect the ability of a seat cushion to dampen the vibration. Limited information is available on the characteristics of higher frequency multi-axis vibration encountered during propeller aircraft operations and the effects of the aircraft seating system on the transmission of this workplace vibration to the occupant.

The objective of this study was to investigate the dynamic characteristics and human perception of higher frequency multi-axis vibration associated with a military propeller aircraft environment. This study is part of a larger investigation to evaluate the effects of higher frequency multi-axis vibration on humans. The aircraft seat was fitted with different cushions to evaluate and compare their effects on the transmission of higher frequency multi-axis vibration. Two postures, back-on and back-off, were included in the study. The approach was to focus on the major frequency components associated with the propeller aircraft propulsion system and evaluate the vibration at the occupant/seat interfaces in each direction. The transmissibility between the floor and each seat interface in the three translational axes was estimated using a flat acceleration spectrum between 1 and 80 Hz. The transmissibility data were used to further evaluate the transmission characteristics of the seat/cushion combinations associated with higher frequency propeller aircraft vibration. Human subjective response was evaluated using a survey of body region perceptions during

exposure to operational signals and to the major frequency components associated with the propulsion system. The guidelines in ISO 2631-1: 1997 were used to predict frequency- and direction-dependent subject sensitivity and to assess comfort in the higher frequency vibration environment.

METHODS AND MATERIALS

Equipment and Instrumentation

Figure 1. Subject Seated in the E-2C Seat

The study was conducted on the Six Degree-of-Freedom Motion Simulator (SIXMODE) (Servotest Systems Limited, England) located at the Air Force Research Laboratory, Human Effectiveness Directorate at Wright-Patterson Air Force Base, Ohio, USA. An E-2C seat system with seat pan and seat back cushions was acquired for the study. Figure 1 illustrates a subject seated in the E-2C seat mounted onto the SIXMODE platform.

Although the operational seat was designed to adjust in the fore-and-aft direction, the seat base was rigidly attached to the platform. The seat could rotate about the vertical axis but was locked in the forward-facing direction during testing. Table 1 lists the six seat cushion configurations tested. Configurations A – E included five seat pan cushions and the original E-2C seat back cushion. Configuration F included an E-2C prototype seat pan cushion (used in Configuration E) and an E-2C prototype seat back cushion. Cushion A, the original E-2C seat pan cushion, was a flat cushion fabricated of

Table 1. Cushion Configurations

Cushion Configuration	Description
A	Original E-2C
B	AH-64 Prototype
C	F/A-22 ACESII
D	Supracor® Slimline
E	E-2C Prototype (Seat Pan Only)
F	E-2C Prototype (Ensemble)

conventional polyurethane foam. A thin stiff material was located at the leading edge of the top of the cushion. The cushion was approximately 5.5 cm in thickness, weighed 1.74 kg, and was covered with fabric. The E-2C seat back cushion, used with Configurations A – E, consisted of a thin layer of polyurethane foam approximately 1 cm in thickness, weighed 0.414 kg including the lumbar support, and was covered with fabric. The separate contoured lumbar support was made of conventional foam about 2-4 cm thick, covered with fabric, and attached to the seat back cushion with snaps. Configuration B was an AH-64 (Apache) prototype seat pan cushion fabricated with a top layer of polyurethane foam about 1 cm thick, a middle layer of rate-sensitive foam about 4 cm thick at the center back, and a bottom layer of stiff foam with air vents about 3.5 cm thick at the center back. An air bladder, designed to provide thigh support, was located inside the cushion toward the front edge. The air bladder was deflated during the study. The cushion weighed 1.70 kg including the inflator hose and bulb, and was covered with a thick wool-type material. Configuration C was an operational seat pan cushion selected for use in the F/A-22 ACESII ejection seat. The cushion was constructed of stiff rate-sensitive foam contoured from 2.5-5.0 cm thick, sealed in a 0.5 cm layer of polyurethane foam, and encased in a fabric cover. It weighed 1.18 kg. Cushion D was a commercially-available seat cushion made of two layers of urethane honeycomb air cells. It was approximately 4 cm thick, weighed 1.23 kg, and included a fabric cover. Configurations E and F were prototype cushions developed for specific use in the E-2C aircraft. The contoured seat pan cushion was comprised of a top layer of about 1 cm of polyurethane foam, a middle layer of rate-sensitive foam, and a thin bottom layer of a stiff, rubber-like material. The seat pan cushion ranged from about 5-9 cm in thickness and weighed 1.57 kg. The seat back cushion was made of rate-sensitive foam about 2.5-5 cm in thickness and contoured for lumbar support. The seat back cushion weighed 1.24 kg. Both cushions were covered with fabric. All seat cushions were attached to the seat pan with double-sided adhesive tape to prevent slippage.

A triaxial accelerometer pack was attached to the floor using double-sided adhesive tape. The packs consisted of three orthogonally-arranged miniature accelerometers (Entran EGAX-24, Entran Devices, Inc., Fairfield, NJ) embedded in a Delrin® cylinder that measured 1.9 cm in diameter and 0.86 cm in thickness, and weighed approximately 5 gm. Triaxial accelerometer pads were secured to the top of the selected cushion at the seat pan and seat back using double-sided adhesive tape and duct tape. Each pad consisted of a flat rubber disk approximately 20 cm in diameter and weighed approximately 355 gm. Embedded in the disk was a triaxial accelerometer pack.

Seven subjects (4 females and 3 males) with mean body weights ranging between 55.6 kg and 99.6 kg participated in the study. Subjects were members of the Impact Acceleration Panel at Wright-Patterson AFB, OH. The study was approved by the Institutional Review Board (IRB) at Wright-Patterson AFB. The subjects were instructed to maintain an upright posture in contact with the seat back (back-on) or not in contact with the seat back (back-off).

Acceleration Data Collection and Processing

Subjects were exposed to two signals representing operational vibration measured at the NFO stations during Loiter flight on the E-2C Hawkeye (Smith, et al., 2001). Loiter represents the mission flight scenario for the aircrew. The vibration spectra associated with both Signal 1 and Signal 2 were characterized by a distinct peak occurring at approximately 18.5 Hz associated with the rotor speed or propeller rotation frequency (PRF) and a distinct peak occurring at approximately 73.5 Hz associated with the blade passage frequency (BPF). Signal 1 showed the highest vibration levels in the X direction of the occupant or the Y direction of the aircraft for both spectral components. The lowest levels occurred in the Y direction of the occupant along the longitudinal axis of the aircraft. Signal 2 showed

some differences in the magnitudes of the peak responses. The most dramatic difference occurred in the Z direction, where the vibration associated with the PRF was notably lower for Signal 1. The X-axis accelerations tended to be lower for Signal 2. In addition, the accelerations were more similar in the X and Z direction for Signal 2. The frequency spectra associated with Signal 1 are illustrated in the Results section.

Subjects were also exposed to sinusoidal vibration in the vicinity of the major frequency components identified in the operational signals. These frequencies included 18.5 Hz (PRF) and 74 Hz (BPF). The sinusoidal exposures were accomplished in each of the three separate translational axes (fore-and-aft or X, lateral or Y, and vertical or Z), and in the combined XYZ axes. The magnitudes of the 18.5 Hz and 74 Hz sinusoidal vibration were similar to the respective peaks associated with Signal 1 in the X direction. The sinusoidal signals were primarily used to conduct the body region perception survey described in Subjective Data Collection and Comfort Assessment.

In order to estimate the transmissibility between the floor and occupant/seat interfaces for the various seat/cushion combinations, subjects were exposed to a flat acceleration spectrum between 1 and 80 Hz at 1.0 ms^{-2} rms in each separate translational axes (X, Y, and Z).

All signals were regenerated at 1024 samples-s^{-1} in the respective axes on the SIXMODE. The acceleration data were collected for 20 s, low-pass filtered at 100 Hz, and sampled at 1024 samples-s^{-1}. MATLAB® was used to estimate the constant bandwidth power spectral density (psd) using Welch's method (Welch, 1967) at the floor, seat pan and seat back. The time histories in each direction were divided into 2-s segments with 50% overlap. A Hamming window was applied to the segments and the resultant power spectral densities averaged for the 20-s exposure. The root-mean-square (rms) acceleration frequency spectra in the fore-and-aft (X), lateral (Y), and vertical (Z) directions (relative to the seated occupant) were calculated as:

$$a_{rmsi} = \sqrt{(a_{psdi} * 0.5)} \qquad (1)$$

where i represents the ith frequency component and 0.5 is the frequency resolution in Hertz (Hz). The 20-s acceleration time histories were also analyzed in one-third octave proportional frequency bands using a modified MATLAB® software program developed by Couvreur (1997).

In addition to evaluating the acceleration level at the two frequency components of interest (PRF and BPF), the overall rms acceleration levels (a_{rms}) were calculated between 1 and 80 Hz in each direction in the frequency domain:

$$a_{rms} = \left[\sum_i a_{rmsi}^2 \right]^{\frac{1}{2}} \quad . \qquad (2)$$

The combined overall acceleration level (a_{xyz}) was calculated as

$$a_{xyz} = \sqrt{a_x^2 + a_y^2 + a_z^2} \qquad (3)$$

where a_x, a_y, and a_z are the overall rms acceleration levels in the X, Y, and Z directions, respectively. The combined overall acceleration level is similar to the point Vibration Total Value described below, but uses unweighted acceleration levels.

The transmissibilities between the floor vibration and the seat pan and seat back vibration were calculated for the exposures to the flat acceleration spectrum between 1 and 80 Hz as

$$H(\omega) = P_{lM}(\omega) \Big/ P_{ll}(\omega) \qquad (4)$$

using the same processing scheme as described for the constant bandwidth spectral estimates (Welch's Method). For transmissibility, upper case letters denote output directions; smaller case letters denote input directions. P_{lM} is the cross-spectrum between the inputs x, y, or z (l) at the floor and the outputs X, Y, or Z (M) at the seat pan and seat back. P_{ll} is the auto-spectrum of the input x, y, or z. For this case, the ordinary coherence, $C(\omega)$, was estimated as follows:

$$C(\omega) = \left| P_{lM}(\omega) \right|^2 \Big/ P_{ll}(\omega) P_{MM}(\omega) \qquad (5)$$

Subjective Data Collection

The body region perception survey was conducted following each exposure, including the two operational signals and the sinusoidal vibration at 18.5 Hz and 74 Hz. The subjects were asked to identify those body regions where the vibration was noticeable. The subjects could identify more than one body region in descending order of sensitivity. Nine body regions were used, including No Specific Location, Face (front of head), Head/Neck (back of head), Upper Back, Chest (including internal), Lower Back, Buttocks, Upper Legs, and Lower Legs (including feet).

Comfort Assessment

The one-third octave seat pan and seat back data (back-on) were weighted in each direction in accordance with the guidelines provided in ISO 2631-1: 1997:

$$a_{wrmsi} = \left[w_{ni} a_{rmsi} \right] \tag{6}$$

where i represents the center frequency component and n represents the particular frequency weighting depending on the measurement site (seat pan or seat back) and direction. The appropriate ISO 2631-1: 1997 multiplying factors, k, were applied to predict the frequency-dependent sensitivity. For assessing comfort, the overall weighted rms acceleration in each direction was calculated between 1 and 80 Hz as

$$a_{wrms} = \left[\sum_i a_{wrmsi}^2 \right]^{\frac{1}{2}} \tag{7}$$

For assessing comfort, the point Vibration Total Value ($pVTV$) was calculated at the seat pan and seat back as

$$pVTV = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2} \tag{8}$$

where k is the multiplying factor associated with a particular measurement site and direction, and a_{wx}, a_{wy}, and a_{wz} are the weighted overall rms acceleration levels in each

respective axis. At the seat pan, k_x=k_y=k_z=1.0. At the seat back, k_x=0.8, k_y=0.5, and k_z=0.4. The overall *VTV* was calculated as the vector sum of the seat pan *pVTV* and seat back *pVTV* (back-on only). The seat pan *VTV* was also calculated using 1.4 as the multiplying factor for the horizontal directions as recommended by ISO 2631-1: 1997 when seat back data are not available for assessing comfort (back-on only). The *VTVs* were used to assess comfort reactions (ISO 2631-1: 1997).

The Repeated measures Analysis of Variance and Bonferroni Comparison Test were used to determine statistical significance ($P<0.05$).

RESULTS

Input and Interface Frequency Spectra

Figure 2 illustrates the input or floor, seat pan, and seat back constant bandwidth frequency spectra in the X, Y, and Z directions (relative to the seated occupant) for two female and two male subjects exposed to Signal 1 with Cushion A. The input signal characteristics were quite similar among all seven subjects. Figure 2 shows that the major frequency components entering the human at the seat interfaces coincide with the PRF and BPF. In addition, in certain directions, there does appear to be evidence of vibration in a broad band between 30 and 60 Hz , with a peak located at approximately 37 Hz, or twice the PRF.

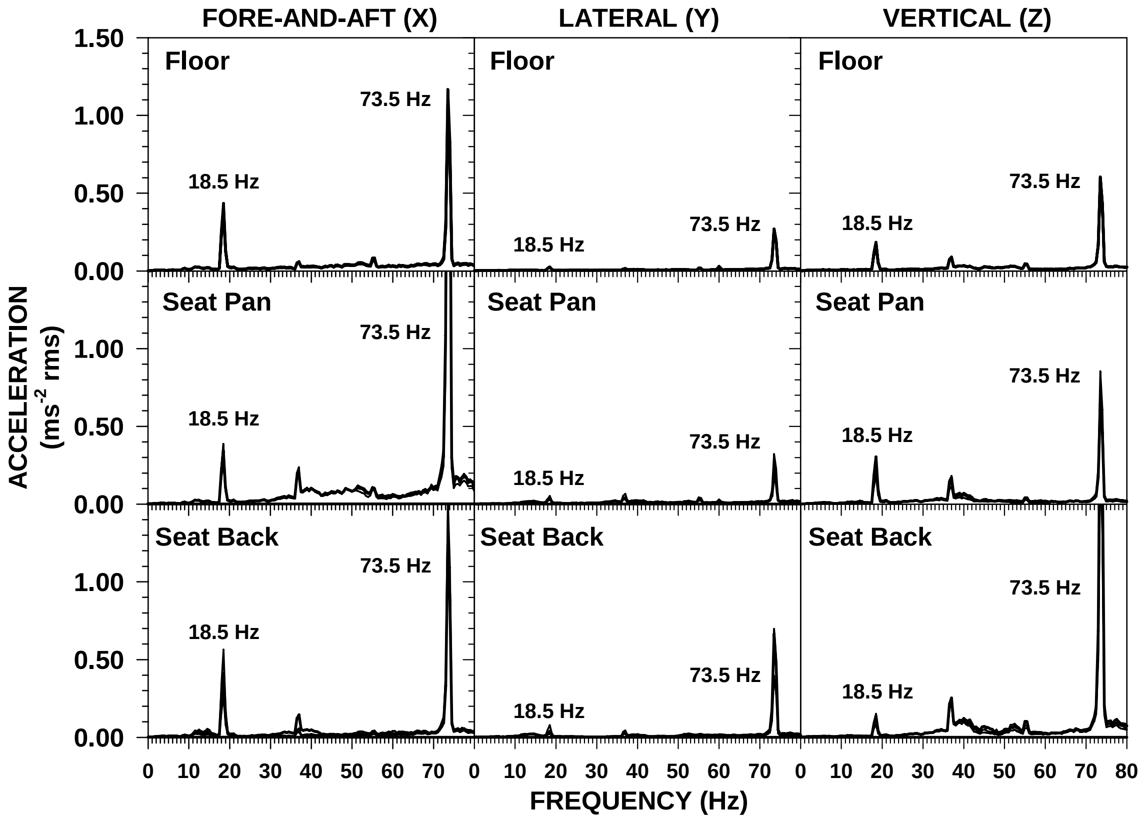


Figure 2. Sample Floor, Seat Pan, and Seat Back Acceleration Frequency Spectra for Two Female (55.6 and 68.1 kg) and Two Male (81.8 and 99.6 kg) Subjects (Signal 1, Cushion A, Back-On Posture)

Occupant/Interface Vibration

Vibration at the Propeller Rotation Frequency (PRF)

Figure 3 illustrates the mean input or floor and seat rms acceleration levels for each cushion and both postures in each of the three orthogonal directions (relative to the seated occupant) at the PRF for exposure to Signal 1. Vibration at the seat back is not included for the back-off posture. For both postures, the highest seat vibration occurred in the X direction. This tendency was similar for exposure to Signal 2, although not as dramatic, particularly at the seat back (back-on only). For both postures, the X-axis seat pan accelerations tended to be lower for Signal 2 as compared to Signal 1, similar to the floor observations, and showed significant damping of the input vibration. Interestingly, the Z-axis seat pan accelerations

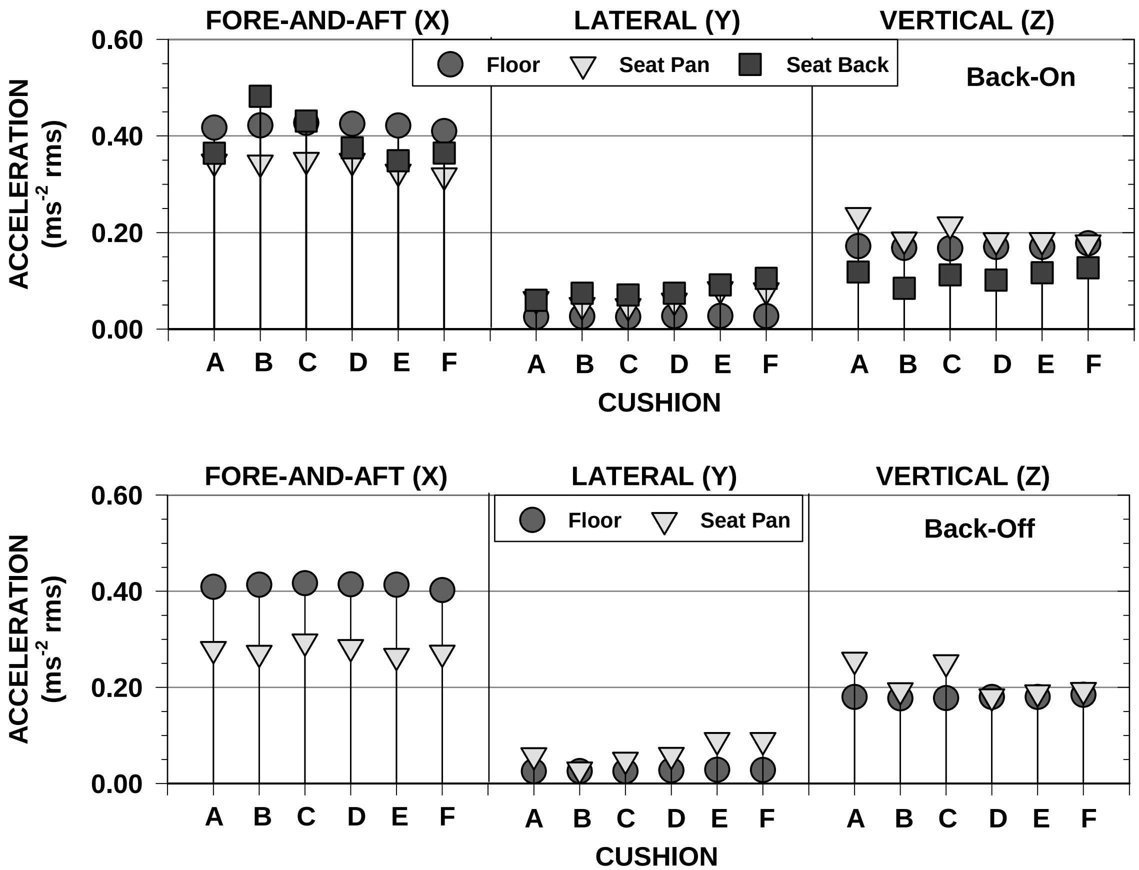


Figure 3. Mean Floor, Seat Pan, and Seat Back Accelerations at 18.5 Hz (PRF) for the Back-On and Back-Off Postures (Signal 1).

tended to be lower for Signal 2 as compared to Signal 1, in contrast to the input or floor accelerations, and showed significant damping of the Z-axis input vibration for all cushions. With the back-on posture, the X-axis seat back accelerations tended to be lower, but the Z-axis seat back accelerations tended to be higher with Signal 2 as compared to Signal 1. In the Z direction, there was some damping of the input vibration at the seat back for both Signal 1 and Signal 2. This damping was significant for both signals.

With the back-on posture, exposures to Signal 1 showed no significant differences in the seat pan accelerations among the cushion configurations at the PRF in the respective X or Y directions. The Y-axis seat pan accelerations were relatively low. In the Z direction, all cushions, except Cushion C, showed significantly lower Z-axis seat pan accelerations as

compared to Cushion A. With the back-on posture, exposures to Signal 2 showed significant differences in the seat pan accelerations among the cushions at the PRF for both the X and Z directions. In the X direction, Cushions E and F showed significantly lower accelerations as compared to Cushion D. In the Z direction, Cushion B showed significantly lower accelerations as compared to Cushions A and C.

With the back-on posture, exposure to Signal 1 showed no significant differences in the seat back accelerations among the cushions at the PRF in the respective X and Y directions. In the Z direction, Cushion B tended to show the lowest seat back accelerations as observed in Figure 3. These results were significant when compared to Cushions A, E, and F. One subject did show relatively high seat back accelerations with Cushions B and C in the X direction. These data were eliminated from the mean values at the seat back in Figure 3. With the back-on posture, Signal 2 showed no significant differences in the seat back accelerations among the cushions in the X, Y, or Z directions. In general, the seat pan and seat back acceleration differences among the cushions at the PRF were not dramatic, regardless of the exposure.

With the back-off posture, there were no significant differences in the seat pan accelerations among the cushions at the PRF in the X or Y direction, regardless of the exposure. The acceleration levels in the Y direction were relatively low. In the Z direction, all cushions but Cushion C showed significantly lower acceleration levels as compared to Cushion A, similar to the results with the back-on posture for Signal 1. This was not the case for Signal 2, where Cushion B showed significantly lower seat pan accelerations as compared to all other cushions.

The most notable posture effect occurred at the PRF in the X direction, where exposure to both signals showed a significant reduction in the X-axis seat pan vibration with the back-off posture (Figure 3).

Vibration at the Blade Passage Frequency (BPF)

Figure 4 illustrates the mean input or floor and seat rms acceleration levels for each cushion and both postures in each of the three orthogonal directions (relative to the seated occupant) at the BPF for exposures to Signal 1. Both postures showed significantly higher X-axis

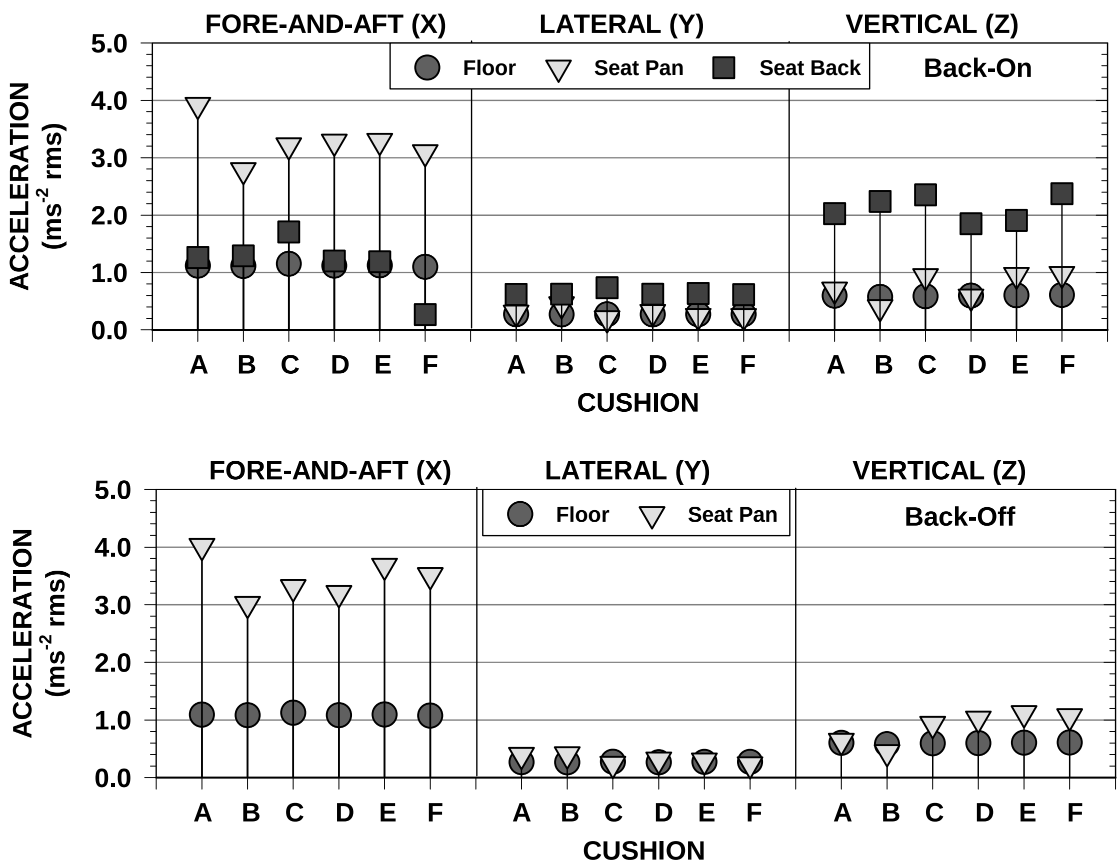


Figure 4. Mean Floor, Seat Pan, and Seat Back Accelerations at 73.5 Hz (BPF) for the Back-On and Back-Off Postures (Signal 1)

seat pan vibration as compared to the input or floor vibration, regardless of the exposure. The Z-axis seat pan accelerations tended to be higher for Signal 1 as compared to Signal 2, similar to the trends observed at the PRF. With the back-on posture, the Z-axis seat back vibration associated with the BPF was significantly amplified relative to the floor and seat pan for exposure to Signal 1 as shown in Figure 4. This was not the case for exposure to Signal 2, where the Z-axis seat back accelerations were markedly lower as compared to

Signal 1 at the BPF and appeared more similar to the input vibration. However, all cushions but Cushion C still showed significantly higher Z-axis seat back accelerations as compared to the input at the floor for Signal 2.

The most significant differences in the vibration among the cushions occurred at the BPF. With the back-on posture, all cushions showed significantly lower X-axis seat pan accelerations as compared to Cushion A. The greatest reduction in acceleration was about 40% with a mean reduction of 20% among all of the cushions. Cushion B tended to show the lowest vibration levels among all of the cushions. This was only significant when compared to Cushion E with Signal 1. Cushion B showed significantly lower X-axis seat pan accelerations as compared to all other cushions with Signal 2. Mixed results occurred at the seat pan in the Y and Z directions for exposures to Signals 1 and 2. As illustrated in Figure 4 for Signal 1, Cushion F showed significantly lower X-axis seat back accelerations as compared to all other cushion configurations, regardless of the exposure.

With the back-off posture, all cushions except Cushion E showed a significant reduction in the X-axis seat pan accelerations as compared to Cushion A with Signal 1. All cushions showed the significant reduction in the seat pan acceleration as compared to Cushion A with Signal 2.

Combined Overall Seat Pan Vibration

Figure 5 illustrates the unweighted combined overall seat pan accelerations for both postures and exposure to Signal 1. For both exposures and postures, the combined overall seat pan accelerations showed cushion effects that were similar to the effects observed in the X direction at the BPF. All of the cushions showed a significant reduction in the seat pan accelerations as compared to Cushion A with the exception of Cushion E with Signal 1 and the back-off posture.

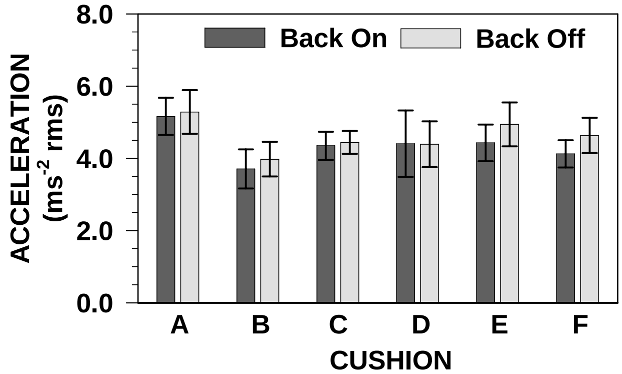
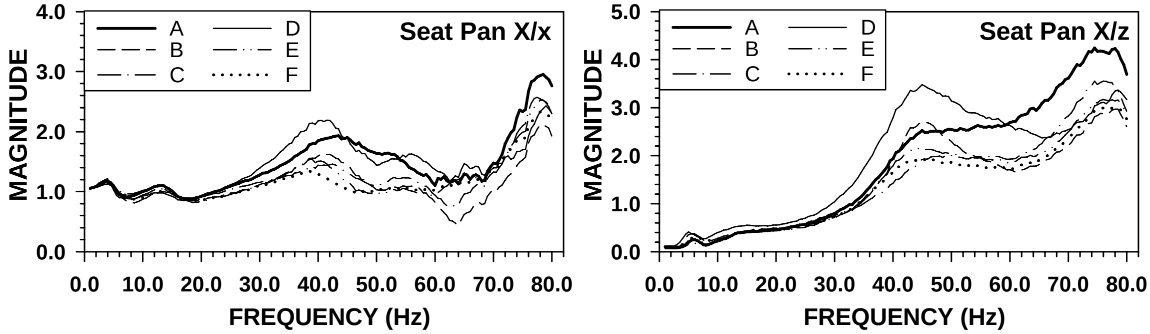


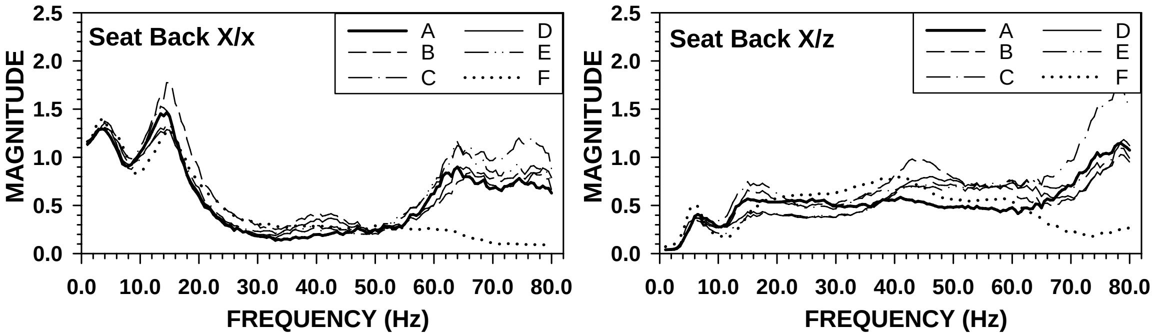
Figure 5. Mean Combined Overall Seat Pan
Accelerations ± One Standard Deviation
for the Back-On and Back-Off Postures (Signal 1)

Flat Spectrum (1-80 Hz) Transmissibility

Figures 6a and 6b illustrate selected transmissibility results at the seat pan and seat back, respectively. Peaks in the transmissibilities were observed in the vicinity of whole-body resonance, as expected, particularly at the seat pan in the Z direction (~5 Hz). Figure 6a shows the substantial transmission of vibration at the seat pan at higher frequencies in the X direction for inputs in the x and z directions (Seat Pan X/x, Seat Pan X/z). At 73.5 Hz (associated with BPF of aircraft), the transmissibilities tended to be the highest for input in the z direction, the means among the cushions ranging from approximately 2.7 to 4.2 (Seat Pan X/z) as compared to a range of 1.4 to 2 (Seat Pan X/x). The Seat Pan X/x and X/z transmissibilities at 73.5 Hz also tended to be higher for Cushion A. For Seat Pan X/x, Cushions B and D showed significantly lower transmissibilities than Cushion A. For Seat Pan X/z, all cushions showed significantly lower transmissibilities as compared to Cushion A at 73.5 Hz, similar to the results obtained for the operational signals at the BPF. Cushion B tended to show the lowest Seat Pan X/x and Seat Pan X/z transmissibilities at 73.5 Hz. Figure 6b shows that the Seat Back X/x and Seat Back X/z transmissibilities were substantially lower for Cushion F at higher frequencies. For Seat Back X/x, this was significant for all cushions at 73.5 Hz. For Seat Back X/z, this was only significant for Cushions A, C, and E at 73.5 Hz. Although not shown, the Seat Back Z/z did show



a. Seat Pan



b. Seat Back

Figure 6. Mean Transmissibilities During Exposure to the Flat Acceleration Spectrum at 1.0 ms^{-2}. Upper case Letter X represents output direction; lower case letters x and z represent input directions. a. Seat Pan, b. Seat Back

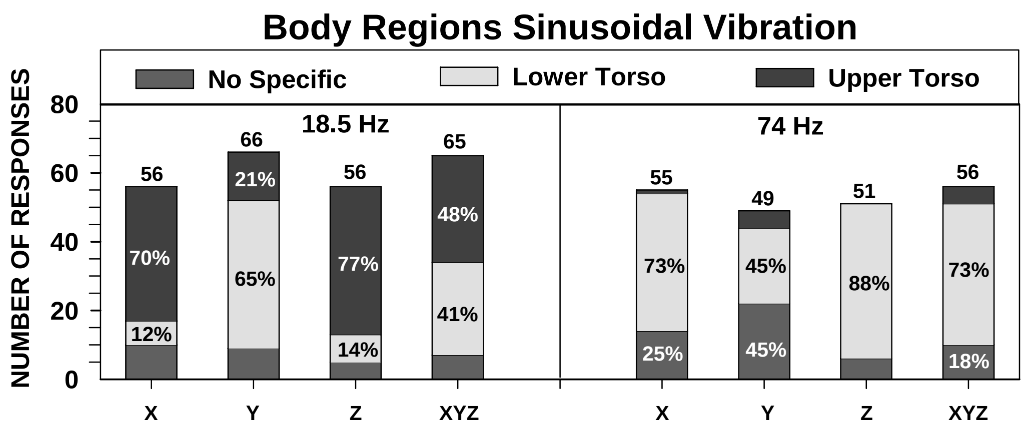
transmissibilities exceeding 1.0 at higher frequencies associated with the BPF. There also appeared to be some influence of the input vibration in the x direction on the seat back vibration in the Z direction (Seat Back Z/x). All coherences were generally quite high, approaching 1.0 across the frequency range of 1 to 80 Hz.

Subjective Effects and Comfort Assessment

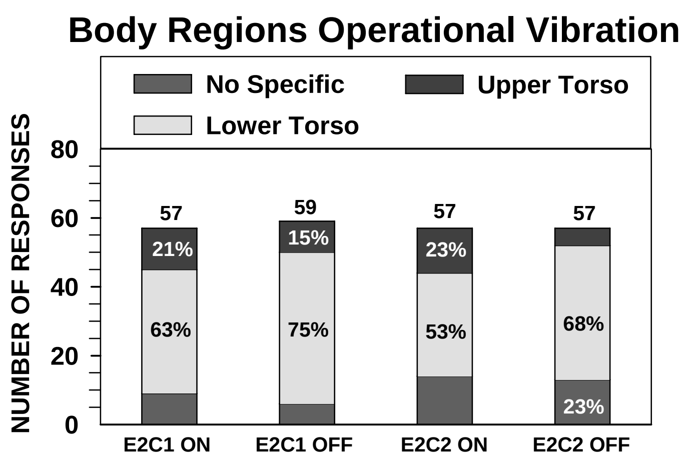
Body Region Perception Survey

The data collected during the body region perception survey were combined into three major groups. The first group included No Specific Location. The second group comprised the upper torso and included the Face, Head/Neck, Upper Back, and Chest. The

third group was the lower torso and included the Lower Back, Buttocks, Upper Legs, and Lower Legs (including feet). The data were pooled since no clear differences were observed among the cushions. Figure 7a illustrates the percentage of responses that fell into the three body region perception groups for the sinusoidal exposures at 18.5 Hz and 74 Hz. The figure includes the total number of responses for the particular vibration direction



a. Sinusoidal Exposures



b. Operational Exposures

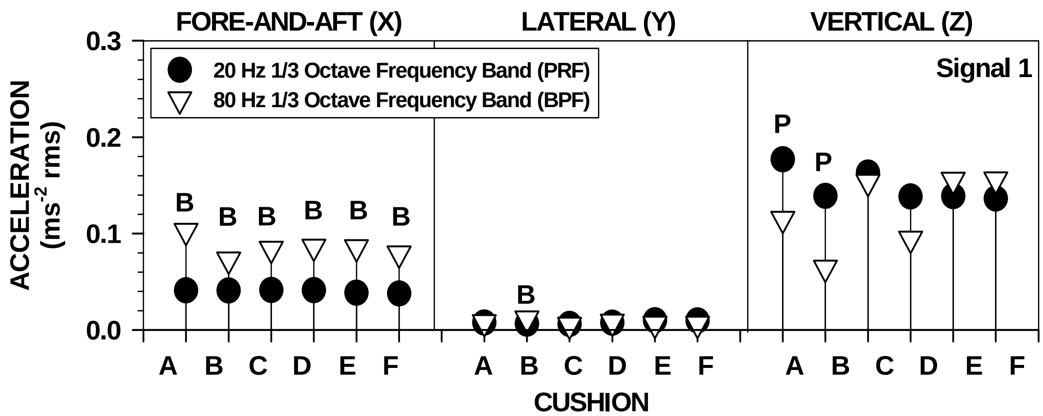
Figure 7. Body Region Perception Percentages. The total responses included for a particular frequency, direction, or operational exposure are annotated above the bars. a. Sinusoidal Exposures, b. Operational Exposures

and frequency. At 18.5 Hz, the subjects sensed or perceived the vibration primarily in the upper torso in all directions except Y. At 74 Hz, the subjects sensed the vibration primarily in the lower torso except in the Y direction, where the responses were equal for the lower

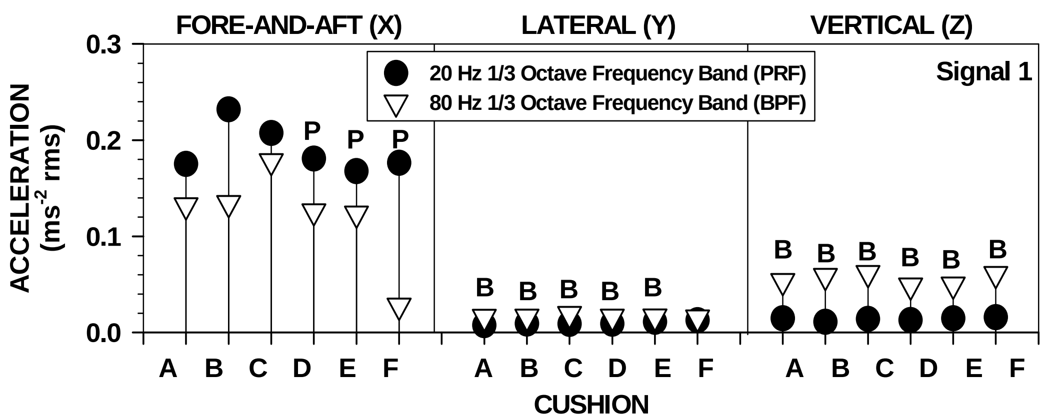
and upper torso. As shown in Figures 3 and 4, the operational vibration levels at the PRF and BPF tended to be quite low in the Y direction. The levels used during the sinusoidal Y-axis exposures were relatively higher. In the lower torso, the vibration was notably felt in the area of the buttocks in contact with the seat. Figure 7b illustrates the percentage of responses that fell into the three groups for exposures to the operational signals with both postures. The subjects primarily felt the operational exposures in the lower torso, similar to the perceptions for the sinusoidal exposures at 74 Hz. This did suggest that the subjects were more sensitive to the frequency component associated with the BPF (73.5 Hz).

Weighted Acceleration Levels and Human Sensitivity

The frequency weightings and multiplying factors given in ISO 2631-1: 1997 suggest that frequency components with similar weighted acceleration levels should be equal with respect to human perception or sensitivity to the vibration. Figure 8 illustrates the mean weighted seat acceleration levels at the center frequency of the respective one-third octave band in the vicinity of the propeller rotation frequency (PRF) (20 Hz) and blade passage frequency (BPF) (80 Hz) for exposure to Signal 1 with the back-on posture. (The multiplying factor for the seat pan was 1.0 in all directions.) Although not statistically evaluated, Figure 8a suggests that the Z-axis vibration would be perceived as being higher than the X-axis and Y-axis vibration at the seat pan, particularly at the PRF. This is in contrast to the results shown in Figure 4, where higher accelerations were measured in the X direction. The weighted X-axis seat pan acceleration levels associated with the BPF were statistically higher as compared to the levels associated with the PRF, suggesting that individuals would perceive the X-axis vibration as being higher at the BPF (annotated by a B in Figure 8). Regardless, as mentioned above, the weighted Z-axis seat pan vibration tended to be higher, particularly at the PRF. For the weighted Z-axis seat pan accelerations, all cushions but two, including the original E-2C seat cushion, showed no statistical difference between the weighted vibration at the PRF and at the BPF. The results for the back-off posture were similar. The relative effects of the weighted frequency components for exposure to Signal 2 were identical to the effects observed for Signal 1.



a. Seat Pan



b. Seat Back

Figure 8. Mean Weighted Acceleration Levels in the 20 Hz and 80 Hz One-Third Octave Frequency Bands Associated with the Propeller Rotation Frequency (PRF) and Blade Passage Frequency (BPF), Respectively, a. Seat Pan, b. Seat Back

Figure 8b suggests that the X-axis vibration at the seat back would be perceived as being higher as compared to the Y-axis and Z-axis vibration. In the X-axis, 50 percent of the cushions for exposure to Signal 1 and all cushions for exposure to Signal 2 showed that the seat back vibration associated with the PRF would be perceived as being higher (annotated with a P). For both exposures, the lower weighted values in the Y and Z directions did indicate that vibration at the BPF would be perceived as being higher compared to the PRF. However, except for Cushion F, the weighted Y- and Z-axis seat back vibration was substantially lower as compared to the X axis.

ISO 2631-1: 1997 Comfort Assessment Using the Vibration Total Value (VTV)

Figure 9 illustrates the seat pan point VTV (using the 1.4 multiplying factor) and the overall VTV for exposure to Signal 1 with the back-on posture. Based on the seat pan

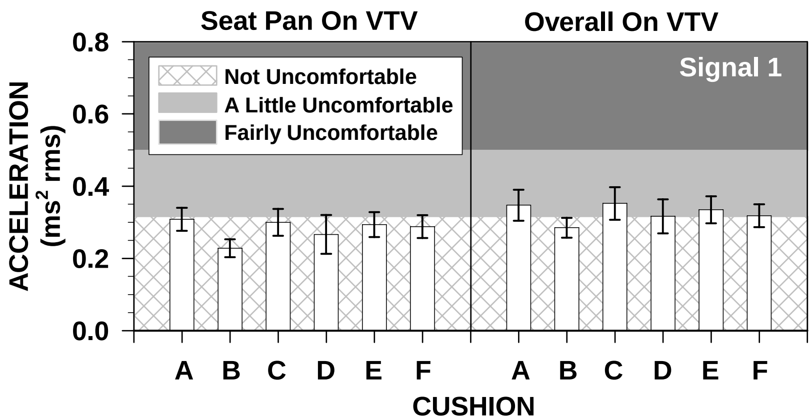


Figure 9. Seat Pan VTV and Overall VTV ± One Standard Deviation for Exposure to Signal 1 and the Back-On Posture

point VTV, three subjects would consider the vibration "a little uncomfortable" using Cushion A with weighted values exceeding 0.315 ms^{-2} rms. No more than two subjects would consider the vibration "a little uncomfortable" for the remaining cushions, and all subjects would consider Cushion B "not uncomfortable." All subjects considered exposure to Signal 2 "not uncomfortable." A larger number of subjects would consider the vibration "a little uncomfortable" when the overall VTV was used for the assessment. Cushion A showed 6 out of 7 subjects, Cushion E showed 5 out of 7 subjects, Cushion C showed 4 out of 6 subjects, and Cushion F showed 3 out of 7 subjects would consider the vibration "a little uncomfortable" when exposed to Signal 1. All subjects would consider Cushion B "not uncomfortable." Only one subject considered exposure to Signal 2 "a little uncomfortable" when using the overall VTV (Cushion A). Statistical analysis of the overall VTV showed significantly lower values for Cushion B compared to Cushions A and C for Signal 1, with no significant differences among the cushions for Signal 2.

For the back-off posture, only the seat pan point VTV was calculated (without the 1.4 multiplying factor). Exposure to Signal 1 did show that up to 3 of the 7 subjects would

consider the vibration to be “a little uncomfortable” (Cushions C and E). All subjects considered exposure to Signal 2 “not uncomfortable”. For both exposures, the back-off posture showed that the seat pan point VTV was significantly lower for Cushion B as compared to all other cushions.

DISCUSSION AND CONCLUSIONS

This study evaluated and compared the dynamic and perceptual characteristics of higher frequency military propeller aircraft vibration in occupants of a military aircraft seat fitted with different cushions and exposed to operational vibration. The results of this study emphasized the significant presence of higher frequency fore-and-aft (X) vibration relative to the seated subject. This vibration occurred in the lateral direction of the aircraft since the occupants were rotated 90 degrees from the longitudinal axis. Specifically, the vibration at the seat pan was observed to be the highest and was significantly greater than the input vibration in the X direction at the BPF (73.5 Hz) regardless of the cushion. The transmissibility data revealed the influence of cross-axis coupling in the seating system on the higher frequency vibration entering the occupant at the seat pan, indicating that the input vibration in the z direction had a greater influence on the vibration measured in the X direction (Seat Pan X/z) than the input vibration in the x direction (Seat Pan X/x).

In the vertical direction, the similarity between the Z-axis seat pan and floor accelerations at the respective frequency components (PRF and BPF) coincided with the transmissibility results, where most cushions showed a transmissibility around 1.0 or lower. Cushion C was included in the Smith and Loyer (2003) study where most cushions showed damping at higher frequencies above 10 Hz. In contrast to the significant fore-and-aft seat pan vibration at the BPF, the results showed a tendency for significant vertical seat back vibration at the BPF. The transmissibility data again showed an effect of cross-axis coupling with x and z vibration inputs at the floor.

Caution should be taken in applying the transmissibility characteristics obtained for the flat acceleration spectrum to the operational exposures. First, the assumption is made that the same transmissibility behavior occurs for the operational exposures regardless of differences in the acceleration energy level and distribution across the frequency range. Second, Figure 2 shows that, regardless of the higher X-axis seat pan transmissibility with z input at the 73.5 Hz, the x input associated with the BPF in the operational exposure is approximately twice the acceleration level of the z input at the floor. A more detailed analysis of the transmissibility characteristics will be the topic of another paper.

According to the results, any of the tested cushions, particularly Cushion B, could significantly reduce the vibration at the BPF relative to the original E-2C seat cushion that was provided with the aircraft seating system (Cushion A). Cushion A was expected to show different characteristics due to its age and condition, being fabricated entirely of conventional foam material, and the lack of any contour. However, the only substantial difference occurred in the X direction at the BPF. It appeared that none of the cushions had a dramatic effect on mitigating the higher frequency vibration. Even the damping effect of Cushions B, C, D, E, and F produced higher vibration at the seat pan compared to the input. The substantial damping of the X-axis vibration at the seat back with the use of the prototype contoured seat back cushion was noteworthy. The separate lumbar support used with the original seat back cushion most likely contributed to the higher X-axis motions. However, even with the design differences between the two seat back cushions, this did not appear to influence vibration in any other direction. It is not clear to what extent the non-rigid seat structure itself may have contributed to the observed responses at the occupant/seat interfaces. The extent, if any, of relative motion between the seat back and seat pan structures was not known since the accelerometer pads were mounted on top of the cushions.

The human body is sensitive to the frequency, direction, and location of the vibration as described in the ISO 2631-1: 1997. Therefore, it is reasonable to base mitigation strategies on human sensitivity or perception of the vibration. The body region perception survey

showed that vibration in the X and Z direction at the PRF would be perceived as being felt the most in the anatomical structures associated with the upper torso, and that vibration in the X and Z direction in the vicinity of the BPF would be felt the most in the lower torso. The subjects reported feeling Signals 1 and 2 in the lower torso, mostly in the buttocks region. Since the Y-axis vibration was quite low, this strongly suggested that the subjects were more sensitive to the BPF component of the vibration during exposures to the operational signals.

The ISO 2631-1: 1997 presents frequency weightings and multiplying factors based on human sensitivity or perception. When applying the ISO guidelines, the highest seat pan vibration would be perceived as occurring in the Z direction, even though the actual measured levels were higher in the X direction. Most cushions showed equal perception of the two frequency components in the Z direction, in contrast to the results of the body region perception survey. The similarity among the weighted seat pan accelerations in the X direction suggested that the occupants would be less sensitive to the cushion mitigation properties observed in the unweighted acceleration levels at the BPF. When applying the ISO guidelines, the highest seat back vibration would be perceived in the X-axis even though the actual measured levels were higher in the Z direction (Signal 1). The similarity in the magnitudes between the weighted Z-axis seat pan accelerations and the weighted X-axis seat back accelerations, particularly at the PRF (Figure 8), calls for a more rigorous approach to mitigating the vibration associated with propeller aircraft, that is, it may not suffice to focus on reducing vibration in a single direction or at a particular frequency component.

The Vibration Total Value for comfort provides a relatively simple approach to evaluating the perception of the vibration exposures by combining the weighted accelerations in the three directions and at the two key seat locations. Based on either the point VTV at the seat pan or the overall VTV, only Cushion B would significantly reduce the perceived vibration compared to most of the tested cushions. There can also be differences in the estimated comfort reactions depending on whether or not the seat back is included (overall VTV) as

shown in Figure 9. (It is noted that the ISO 2631-1: 1997 recommends the inclusion of the weighted feet acceleration in the calculation of the VTV that was not measured in this study.) The higher overall VTV compared to the seat pan VTV obtained in this study strongly suggested that contact with the seat back would reduce comfort compared to the back-off posture. However, other factors such as muscle strain associated with the unsupported posture may contribute to discomfort with the back-off posture, particularly during prolonged exposures. In addition, the overall VTV did not reflect an effect of the significant reduction in the seat back acceleration observed with the prototype seat back cushion (Cushion F) in the X direction. It is noted that the Navy report (Loomis, 1999) implied that the NFOs would consider the vibration more than “a little uncomfortable.” The guidelines given in the ISO are based on approximate comfort reactions in public transport vehicles and are independent of time. These criteria may not effectively reflect the perception of vibration at higher frequencies in military propeller aircraft, particularly during prolonged missions.

The development of effective mitigation strategies requires detailed knowledge of the dynamic vibration characteristics, including the frequency, magnitude, direction, and location, and the relationship of these characteristics to subjective effects and human perception. Current guidelines do provide the basic tools for assessing workplace vibration and for evaluating these relationships. The results of this study suggest that current guidelines may not optimally reflect these relationships for exposures to higher frequency vibration encountered during the operation of propeller aircraft as supported by Smith (2006). Even though seat and cushion designs may be able to significantly reduce the vibration of specific frequency components, the perceived reduction is the key to effective mitigation. Newer seat designs, including active or semi-active vibration isolation mechanisms, may provide greater mitigation of higher frequency vibration as compared to a cushion alone. It is cautioned that a seating system or cushion that reduces vibration transmission to the occupant doesn’t necessarily imply that the seat is more comfortable, and vice versa. The challenge is to design comfortable seating systems that are lightweight, crashworthy, and capable of reducing the transmission of vibration. Other strategies should

not be ignored; periodic balancing of the propellers has been shown to reduce the vibration at the PRF in certain aircraft (Smith, 2006).

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the funding agency.

REFERENCES

Burmeister K, Thoma WK, 1986. Relationship between backache and flying duty in jet- and prop-pilots demonstrated by a flying wing. Advisory Group for Aerospace Research and Development, Conference Proceedings, Aerospace Medical Panel Specialists' Meeting. Pozzuoli, Italy, AGARD-CP-378, 5A-1–16.

Couvreur C, 1997. Internet MATLAB computer file. Belgium: Faculte Polytechnique de Mons.

Fairley TE, Griffin MJ, 1986. A test method for the prediction of seat transmissibility. Society of Automotive Engineers, International Congress and Exposition. Detroit, Michigan, USA, SAE Paper No. 860046.

International Organization for Standardization (ISO), 1997. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. Geneva, ISO 2631-1:1997.

Loomis TA, Hodgdon JA, Hervig L, Prusaczyk WK, 1999. Neck and back pain in E-2C Hawkeye aircrew. Naval Health Research Center. San Diego, CA, Report No.: 99-12.

Pope MH, Wilder DG, Donnermeyer DD, 1986. Muscle fatigue in static and vibrational seating environments. Advisory Group for Aerospace Research and Development, Aerospace Medical Panel Specialists' Meeting. Pozzuoli, Italy, AGARD-CP-378, 25-1-10.

Pope MH, Broman H, Hansson T, 1989. The dynamic response of a subject seated on various cushions. Ergonomics 32(10), 1155-66.

Seris H, Auffret R, 1967. Measurement of low frequency vibrations in big helicopters and their transmission to the pilot. Advisory Group for Aerospace Research and Development, Aerospace Medical Panel, NASA Technical Translation NASA TT F-471.

Shanahan DF, Reading TE 1985. Helicopter pilot back pain: A preliminary study. Army Medical Research & Development Command, Fort Detrick. Frederick, Maryland, USA, USAARL Report No.: 85-13.

Smith SD, 1997. Cushions and suspensions: Predicting their effects on the biodynamic responses of humans exposed to vertical vibration. Heavy Vehicle Systems, Int. J. of Vehicle Design 4(2-4), 296-316.

Smith SD, 1998. The effects of prototype helicopter seat cushion concepts on human body vibration response. Journal of Low Frequency Noise, Vibration and Active Control 17(1), 43-53.

Smith SD, Artino AR Jr., Newman RJ, Hodgdon JA, 2001. Human vibration analysis in a military propeller-driven aircraft. 36th United Kingdom Group Meeting on Human Response to Vibration, QinetiQ. Farnborough, England.

Smith SD, Loyer CM, 2003. The effects of military aircraft seat cushion concepts on human vibration response. 41st Annual SAFE Symposium. Jacksonville, FL, USA.

Smith SD, 2006. Seat vibration in military propeller aircraft: characterization, exposure assessment, and mitigation. Aviation, Space, and Environmental Medicine 77(1), 32-40.

Welch PD, 1967. The use of Fast Fourier Transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. IEEE Trans. Audio Electroacoust. AU-15, 70-3.